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Estimation of Suspended Sediment Trapping Ratio for Channel Infilling and Bypassing

by Magnus Larson and Nicholas C. Kraus

PURPOSE: The Coastal and Hydraulics Engineering Technical Note (CHETN) herein describes a method for estimating the percentage of sand-sized material placed in suspension by breaking waves and carried by a cross-channel current to either fall into a navigation channel or travel across it. Required inputs are channel width and depth, depth in the vicinity of the channel, depth-averaged current velocity perpendicular to the channel, and sediment fall speed. The procedure is applicable to inlet entrances that experience breaking waves. The percentage of material deposited into or passing a channel is an input to the channel infilling model described in Kraus and Larson (2001).

CALCULATION METHOD: Navigation channels issuing from an inlet intercept sediment that is moving alongshore (Figure 1). The longshore transport may be generated by wave- and wind-generated currents, and by the longshore component of the flood-tidal current entering the channel. Sediment can pass over the channel by moving in suspension, and it can be deposited on the channel bottom and, possibly, resuspended and transported out of the channel (Kraus and Larson 2001). This Technical Note presents a method for estimating the percentage of suspended material transported alongshore (perpendicular to a channel) that will be deposited in a channel (the trapping ratio), from which the amount passing over the channel is determined. The following assumptions are made:

a. Transport occurs mainly in the surf zone, for example, in Sections 2, 3, and 4 in Figure 1. This assumption will be removed in later development of the model to describe deep-draft channels and transport seaward of the surf zone.

b. Deposition in the channel is controlled by gravity through the sediment fall speed V_f. Upward diffusion by turbulence and vertical currents in the channel is neglected; giving a conservative estimate of infilling.

c. The flow across the channel can be described by a simple parameterization based upon continuity (recirculation in the channel is neglected).

d. The velocity is uniform through the water column.

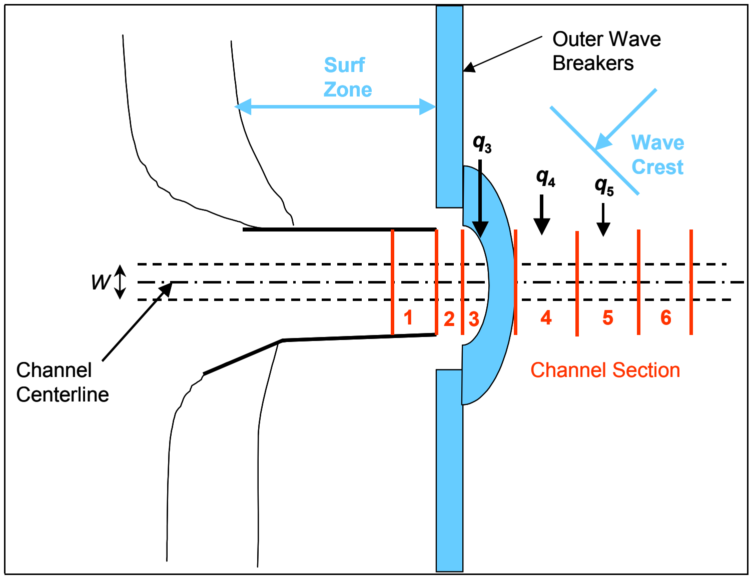

Figure 1. Planview sketch for channel transport sections

Transport at Channel: The transport rate q_{in} at the updrift edge of the channel may be calculated from the depth-averaged longshore current (current uniform through the water column) and the suspended sediment concentration distribution according to the product,

$$q_{in} = \int_0^{h_a} U_a C(z) dz = U_a \int_0^{h_a} C(z) dz \tag{1}$$

where U_a = depth-averaged velocity normal to the channel, $C(z)$ = sediment concentration, z = elevation from the surrounding (ambient) bed, and h_a is the ambient depth adjacent to the channel (Figure 2). The transport rate per unit length of channel may have to be divided into sections as shown in Figure 1, according to the current, ambient depth, channel depth, and presence of wave breaking.

Empirically, the sediment concentration profile in the surf zone has been found to decrease with elevation from the bottom as an exponential shape,

$$C(z) = C_b \exp\left(-\lambda z / h_a\right) \tag{2}$$

where C_b = concentration at the bed, and λ = dimensionless empirical suspended-sediment decay coefficient (Kraus and Dean 1987). The transport rate of sediment suspended to a certain level z_s above the ambient bed adjacent to the channel is then found by integration to that elevation as:

$$q_{in}(z_s) = U_a \int_0^{z_s} C_b \exp\left(-\lambda z / h_a\right) dz = \frac{U_a C_b h_a}{\lambda}\left[1 - \exp(-\lambda z_s / h_a)\right] \tag{3}$$

If $z_s = h_a$, the total transport through the water column is obtained:

$$q_{in}(h_a) = \frac{U_a C_b h_a}{\lambda}\left[1 - \exp(-\lambda)\right] \tag{4}$$

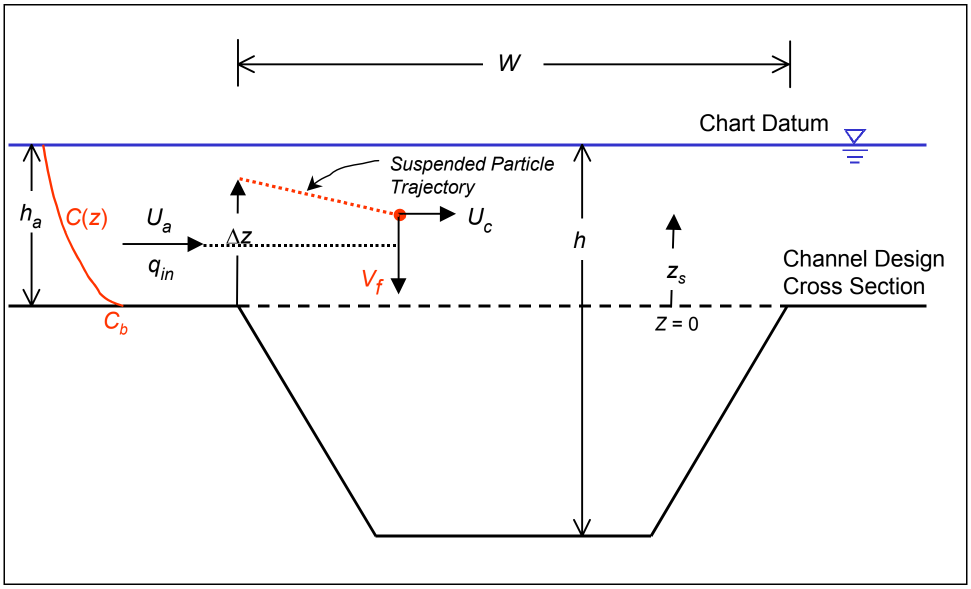

Figure 2. Definition sketch for terminology

The advective velocity across the channel U_c can be estimated from the continuity equation given the velocity and ambient depth upstream of the channel and the average depth h_c in the channel:

$$U_c = \frac{h_a}{h_c} U_a \tag{5}$$

Therefore, if a suspended sediment particle of fall speed V_f is transported with advective velocity U_c across a channel of width W, it will fall a vertical distance Δz given by:

$$\Delta z = \frac{W}{U_c} V_f = \frac{h_c}{h_a} \frac{V_f}{U_a} W \tag{6}$$

Particles suspended to level Δz or greater at the updrift end of the channel will pass over the channel, whereas particles with elevations less than Δz will fall into the channel and be deposited there.

The ratio p of the total suspended transport q_{in} that is trapped by the channel can be estimated from:

$$p = \frac{q_{in}(\Delta z)}{q_{in}(h_a)} = \frac{1-\exp(-\lambda \Delta z / h_a)}{1-\exp(-\lambda)} = \frac{1-\exp\left(-\lambda \frac{h_c W}{h_a^2} \frac{V_f}{U_a}\right)}{1-\exp(-\lambda)} \tag{7}$$

With the above expressions, p, which can be called a "trapping ratio," can be estimated from the idealized geometry of the channel (channel width and average depth at the particular time of the calculation), sediment fall speed, upstream current speed and depth, and decay coefficient λ of the concentration profile.

Table 1 lists sediment fall speeds for quartz grains of typical diameters and for different water temperatures, which will change water viscosity and, therefore, sediment fall speed.

Table 1
Selected Values of Fall Speeds (m/s) for Quartz Sand Particles of Specified Diameters (after Hallermeier (1981))

Temp. deg C	Grain Size, mm										
	0.15	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.50**	**0.60**	**0.80**	**1.00**	**2.00**
10	0.015	0.023	0.029	0.035	0.042	0.048	0.062	0.075	0.104	0.132	0.189
20	0.018	0.025	0.032	0.039	0.046	0.054	0.069	0.084	0.115	0.133	0.189
30	0.020	0.027	0.035	0.043	0.051	0.059	0.075	0.092	0/119	0/133	0.189

Suspended Sediment Decay Coefficient: The decay coefficient λ has been measured to have a representative value of 1.65 with standard deviation of 0.68 for surf-zone sand with median grain size in the range of 0.14 to 0.22 mm (Kraus and Dean 1987). Because λ is grain-size dependent, in this section a rational method is presented for extending the result to other grain sizes.

If the time-averaged turbulence intensity is homogeneous through the water column, which is a reasonable representation of a surf zone or area of breaking waves, it is known that the vertical distribution of the sediment concentration is proportional to the quantity $\exp[-(V_f / \varepsilon_s) z]$, where ε_s = sediment-mixing coefficient. Adopting concepts of Battjes (1975), the sediment-mixing coefficient can be estimated as,

$$\varepsilon_s = k_d \left(\frac{D}{\rho}\right)^{1/3} h_a \tag{8}$$

where k_d = dimensionless empirical coefficient expected to be independent of grain size, D = energy dissipation produced by the breaking waves, and ρ = density of water. The standard expression $\exp[-(V_f / \varepsilon_s) z]$ becomes,

$$C(z) = C_b \exp\left(-\frac{V_f}{k_d (D/\rho)^{1/3}} \frac{z}{h_a}\right) \tag{9}$$

and comparison of Equation 9 with the empirical Equation 2 gives the decay coefficient λ as:

$$\lambda = \frac{V_f}{k_d (D/\rho)^{1/3}} \tag{10}$$

The dissipation D can be estimated if the nearshore profile updrift the channel has an approximate equilibrium shape. The development of Dean (1977) then gives the energy dissipation as:

$$\frac{D}{\rho} = \frac{5}{24} g^{3/2} \gamma_b^2 A^{3/2} h_a \tag{11}$$

where γ_b = breaker index (0.8), g = acceleration due to gravity, and A = equilibrium profile shape parameter, which Kriebel, Kraus, and Larson (1991) showed could be estimated by:

$$A = \frac{9}{4} \left(\frac{V_f^2}{g} \right)^{1/3} \tag{12}$$

Substituting the expressions for D/ρ and A into λ yields:

$$\lambda = \frac{3}{4k_d} \left(\frac{V_f^2}{g h_a} \right)^{1/3} \tag{13}$$

Equation (13) determines λ as a function of the sediment fall speed and ambient depth, and it is expected to have the correct functional dependencies. Quantitative accuracy must be determined empirically through the value of k_d, which is expected to be independent of environmental factors. Based on the sediment streamer trap data of Kraus and Dean (1987) for nominal 0.2-mm particle size sand, $k_d \cong 0.03$. The quantity $V_f / \sqrt{g h_a}$ appearing in Equation 13 is a Froude number. For typical sand sizes with fall speeds in the range of 0.02 to 0.06 m/s (Table 1), and typical ambient depths of 1 to 10 m, this quantity is in the range of 10^{-2} to 10^{-3}.

Figure 3 plots values of p (in percent) as a function of the argument $h_c W V_f / (h_a^2 U_a)$ in Equation 7 for values of the Froude number $Fr = V_f / \sqrt{g h_a}$ ranging from 0 to 0.02 in four steps of 0.005 and k_d =0.03. For sand-sized and finer sediments, Fr is expected to be small, and values of p will lie close to a straight line. A small value on Fr implies a small value of λ (Equation 13), describing a concentration profile that is approximately uniform through the water column. If Fr approaches zero (i.e., $\lambda \rightarrow 0$), the trapping ratio p will be close to $h_c W V_f / (h_a^2 U_a)$, which corresponds to the portion of the water column upstream of the channel that Δz constitutes. However, because the quantity $h_c W V_f / (h_a^2 U_a)$ contains Fr, the limit $Fr = 0$ implies that this quantity is zero as well. Thus, in Figure 3, the line labeled "0+" denotes an Fr-value slightly greater than zero. In this limit, for which $Fr = 0+$ (i.e., λ=0), the trapping ratio will be

$p = h_c W V_f / (h_a^2 U_a)$. If the calculated value of $h_c W V_f / (h_a^2 U_a)$ is larger than 1, then $p = 1$, and all material will fall into the channel.

If p-percent of the suspended material at a given instant is trapped in the channel, then (1-p) percent bypasses the channel by being advected over it. Kraus and Larson (2001) describes how material may also be resuspended and transported out of a channel, thereby increasing the amount bypassed.

The depth-averaged current velocity perpendicular to the channel should be employed for predicting the trapping ratio. If the current approaches the channel at an angle θ with respect to the orientation of the channel (i.e., for a perpendicular current θ = 90 deg), the current should be divided by sin θ before it inserted as U_a in Equation 7. This result indicates that the trapping ratio increases because the distance traveled for the sediment particles across the channel becomes longer (or equivalently, the component of the incident current transporting the particles across the channel becomes smaller). If there is a uniform current along the channel axis during its crossing of the channel, the end result of consideration of the processes is that there is no change in the trapping ratio. Although, the distance the sediment particles travel increases, so does the speed, and the two processes cancel.

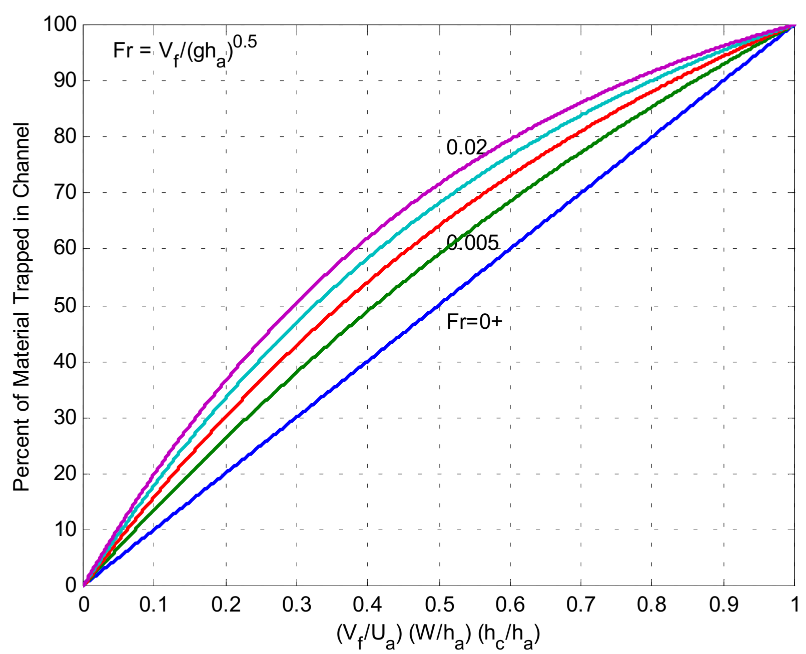

Figure 3. Percentage of sediment falling into the channel

EXAMPLES: The preceding development provides a means of estimating the percentage of suspended material that may fall into a channel (or which may bypass a channel) based on sediment fall speed, geometry of the channel, and the speed of the upstream flow crossing the channel. Here, two examples are given to illustrate applications of this information.

Example 1: Material trapped by or crossing a channel during (a) typical surf conditions, (b) and during a storm.

Given: Channel width W = 30 m; channel depth h_c = 4.5 m; average ambient depth h_a = 3 m; sediment grain size = 0.2 mm. During typical surf conditions, U_a =0.1 m/s and nearshore wave height is 1 m; during stronger storms, U_a =1 m/s and nearshore wave height is 4 m.

Find: The relative percentages of suspended material deposited into and bypassing the channel for that portion of the channel located in the surf zone.

Solution: (a) Typical wave condition: Waves of 1-m height will break in water depth of about 1.3 m, or in depths well shoreward of the area of interest at 3-m depth and seaward of the jetties. However, because of the wave current interaction and the presence of the ebb shoal in the vicinity of the channel, wave breaking is observed to occur intermittently, suspending sediment. Therefore, we proceed. Consulting Table 1, for 0.2-mm sand at 20-deg C, we have V_f = 0.025 m/s, giving:

$$Fr = V_f / \sqrt{gh_a} = 0.025 / \sqrt{9.8 \times 3} = 0.0046\,,$$

and

$$h_c W V_f / (h_a^2 U_a) = 4.5 \times 30 \times 0.024 / (9 \times 0.1) = 3.75$$

Calculating Equation 7 or entering Figure 2, one finds that p >1 for any value of Fr, so p = 100 percent, and all the material falls into the channel for this condition.

(b) Storm condition: Waves of 4-m height will be breaking all around the channel. For this situation:

Fr remains as previously described, 0.0046, and

$$h_c W V_f / (h_a^2 U_a) = 4.5 \times 30 \times 0.025 / (9 \times 1) = 0.375$$

Calculating Equation 7 or entering Figure 2 for the curve Fr = 0.005, p = 46 percent, which means that 1-p = 54 percent of the material passes the channel. It is again noted that not all suspended material that falls into the channel will remain there. Some portion will be resuspended and carried out of the channel, thereby increasing the percent bypassed.

Example 2: Determine the possibility that a sediment plume viewed in an aerial photograph consists of sand bypassing an inlet.

Given: An aerial photograph at an inlet indicates that a sediment cloud or plume, evident by brown color observed on the background of green and white turbulent water, sometimes appears in the surf zone under typical wave conditions (wave height less than 1 m) that follow after a storm. The plume bypasses both jetties of the inlet entrance and continues alongshore for a distance of 200 m past the updrift jetty, where the plume originates. The water depth near the ends of the jetties is about 4 m, and the channel depth is 6 m. The grain size at this beach is relatively fine, 0.17 mm, and has a fall speed of 0.02 m/s. The typical longshore current speed under fair-weather wave conditions is estimated to be 0.2 m/s, a fairly strong current because of the strong longshore component of the wind at this site.

Find: If it is assumed that the sediment plume can be observed half way through the water column, is it possible that the downdrift portion of the plume consists primarily of 0.17-mm sand?

Solution: Under typical wave conditions, waves cannot break in the channel, and resuspension will be minor. Therefore, we assume the suspended sand originates from the surf zone and is carried by the rip current along the updrift jetty to be captured again by the wind-generated longshore current and transported past the jetties. We take Δz =2 m to be the maximum elevation in the water column that can be observed downdrift and assume some 0.17-mm particles are present at the water surface at the updrift (starting) end of the plume. Then by Equation 6, interpreting the distance W as the maximum length of travel,

$$W = \frac{h_a}{h_c}\frac{U_a}{V_f}\Delta z = \frac{4}{4}\frac{0.2}{0.02}2 = 20\text{ m}$$

In this calculation, we set the ratio $h_a/h_c = 1$ to maximize the distance. The fine sand suspended to the water surface and carried by a 0.2-m/s current can only travel 20 m before dropping below 2 m in the water column. Therefore, it is concluded that the surface portion of the plume observed in the photograph must consist of fine material such as clay that has small fall speed and of organic material that floats. Because such plumes can appear after a storm, it may be that the material consists of clay and organic particles washed into the ocean during the runoff caused by the storm.

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